

# **On the Relationship Between Solar Wind Speed, Geomagnetic Activity, and the Solar Cycle Using Annual Values**

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## **LIST OF ACRONYMS**

IP	interplanetary
PI	prediction interval
TP	Technical Publication



## NOMENCLATURE

$aa$	the $aa$ geomagnetic index
$\langle aa \rangle$	cyclic average of $aa$
$aa_I$	residual component of the $aa$ index, equal to $aa - aa_R$
$\langle aa_I \rangle$	cyclic average of $aa_I$
$aamax$	$aa$ index maximum
$aamin$	$aa$ index minimum
$cl$	confidence level
$R$	sunspot number
$\langle R \rangle$	cyclic average of $R$
$Rmax$	sunspot maximum
$Rmin$	sunspot minimum
$r$	linear correlation coefficient
$r^2$	coefficient of determination
$se$	standard error of estimate
$v$	solar wind speed
$x$	independent variable
$y$	regression equation



## TECHNICAL PUBLICATION

# ON THE RELATIONSHIP BETWEEN SOLAR WIND SPEED, GEOMAGNETIC ACTIVITY, AND THE SOLAR CYCLE USING ANNUAL VALUES

## 1. INTRODUCTION

In order to explain the late-occurring geomagnetic peak in solar cycles, Feynman<sup>1</sup> suggested decomposing the *aa* geomagnetic index into two components—one that is in phase and correlated directly with the sunspot cycle, the leading sporadic component, and the other that is out of phase and associated with interplanetary disturbances from the Sun, the residual or following recurrent component, which usually peaks after sunspot maximum (the exceptions are cycles 12 and 13) just before the next cycle's sunspot minimum.<sup>2–5</sup> Following Feynman's approach, Hathaway and Wilson<sup>6,7</sup> decomposed the *aa* geomagnetic record and used the late-cycle recurrent peak to forecast the expected size of the next sunspot cycle (cycle 24), using both the observed and adjusted records of the *aa* index, where the adjusted record is one that compensates for changes in the repositioning of the magnetometers prior to 1957 that are used in the determination of the *aa* index. (See also Svalgaard, Cliver, and Le Sager.<sup>8</sup>) From their studies, it was determined that cycle 24 should be expected to be a cycle of larger than average size, comparable to cycles 21 and 22, the second and third largest cycles of the modern era. (See also Dikpati, de Toma, and Gilman.<sup>9</sup>)

It has long been believed that there should be a good correlation between geomagnetic activity and solar wind speed<sup>10</sup> and, indeed, for periods of high coverage, a strong correlation has been found.<sup>11</sup> Also, it has been found that a general increase in the *aa* index has occurred between 1868 and 2006, where this increase has been attributed to an increase in the strength of the polar magnetic field of the Sun.<sup>12</sup>

In this Technical Publication (TP), the relationship between solar wind speed, geomagnetic activity (the *aa* index), and the solar cycle is reexamined using annual averages, where the solar wind speed is determined using the Omni-merged, 1-hr, 1 AU interplanetary (IP) data <<http://cdaweb.gsfc.nasa.gov>>.<sup>13</sup> This is the first of a two-part study of solar wind and the geomagnetic/solar cycle.

## 2. RESULTS AND DISCUSSION

Figure 1 displays the variation of annual averages of (a) sunspot number  $R$  and (b) the adjusted  $aa$  index for the interval 1860–2006, where the adjusted  $aa$  index<sup>7</sup> is merely the observed  $aa$  value for the interval 1957–2006 and the observed value plus 3 nT for the interval 1868–1956. Although Nevanlinna and Kataja<sup>14</sup> have extended the  $aa$  index for two additional solar cycles (1844–1867) using hourly declination readings at the Helsinki magnetic-meteorological observatory (1844–1880), these data have not been used in this TP. The thin, vertical lines mark the sunspot minimum years and the numbers refer to sunspot cycles 10–23, where cycle 23 is the current sunspot cycle that began in 1996. While sunspot cycles usually have a single, well-defined peak ( $R_{max}$ ) that follows sunspot minimum ( $R_{min}$ ) by 3–5 yr when described using annual averages, the geomagnetic cycle typically has multiple peaks, with the largest ( $aamax$ ) usually occurring during the declining portion of the sunspot cycle (as previously mentioned, the exceptions are cycles 12 and 13), just prior to the sunspot minimum of the following cycle. Also, the minimum value of the geomagnetic index ( $aamin$ ) almost always has occurred in the year following the sunspot minimum year. (The exceptions are cycles 14, 15, and 19, which had  $aamin$  and  $R_{min}$  occurring contemporaneously, and cycle 21, which had  $aamin$  occurring in 1980, some 4 yr past  $R_{min}$  and 1 yr past  $R_{max}$ , although a slightly larger local minimum value was seen at 1 yr past  $R_{min}$ ; the  $aamin$  value for cycle 11 likely occurred during the sunspot minimum year of 1867 and not 1868.)

From figure 1,  $R_{min}$  is found to have varied between 1.4 (cycle 15) and 13.4 (cycle 22), having a 90% prediction range of  $7 \pm 6.7$  for the given sample size of 13 cycles. Also,  $R_{max}$  is found to have varied between 63.5 (cycle 14) and 190.2 (cycle 19), having a 90% prediction range of  $117.5 \pm 70.9$ . The ratio (not shown) of  $R_{max}$  to  $R_{min}$  for the past 13 solar cycles is found to have varied between 10.38 (cycle 20) and 74.21 (cycle 15), having a 90% prediction range of  $22.3 \pm 31.89$ . The value of  $R$  in 2006 measured 15.2, a value that lies just outside the 90% prediction range for  $R_{min}$ . Hence, the sunspot minimum year for cycle 24 likely will occur in 2007 (the annual average for 2007 has recently been determined to be 7.6, well within the 90% range for  $R_{min}$ ), or possibly 2008 if cycle 24 turns out to be a slow riser.

Likewise, from figure 1,  $aamin$  (in the vicinity of sunspot minimum) is found to have varied between 9 (cycle 14) and 20.2 (cycles 19 and 21; cycle 21 actually had a lower  $aamin$  in 1980 (18.5), well after its sunspot minimum year of 1976), having a 90% prediction range of  $15.2 \pm 7.1$  for the given sample size of 12 cycles. (Cycle 11 is not included since its  $aamin$  probably occurred in 1867, before the start of the  $aa$  record.) Also,  $aamax$  is found to have varied between 20.5 (cycle 14) and 37.1 (cycle 23), with all cycles from cycle 18 onward having an  $aamax \geq 30.3$ . The 90% prediction range for  $aamax$  is  $29.7 \pm 8.1$ . The ratio (not shown) of  $aamax$  to  $aamin$  for the past 12 solar cycles is found to have varied between 1.62 (cycle 19) and 2.59 (cycle 12), having a 90% prediction range of  $2.03 \pm 0.6$ . The value of  $aa$  in 2006 measured 16.2, a value within the 90% prediction range for  $aamin$ , and the value of  $aa$  for the first 7 mo of 2007 has averaged 15.6. Excluding cycles 12 and 13, which had  $aamax$  that preceded  $R_{max}$  by 1 yr,  $aamax$  is found to have occurred after  $R_{max}$ , on average, by about 3 yr (the range is 2–6 yr). (Cycles 12 and 13 had slightly smaller local  $aamax$  values after  $R_{max}$ , by 3 and 1 yr, respectively.)

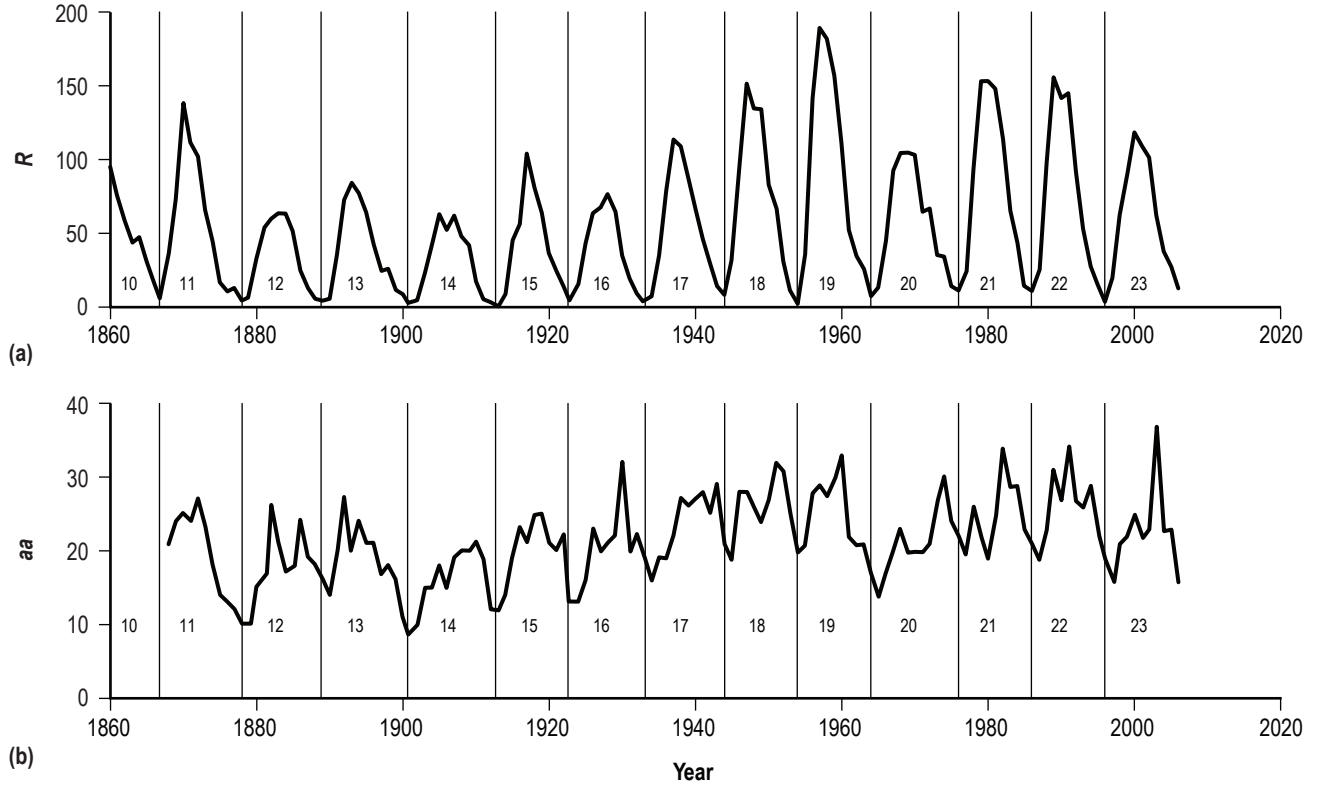


Figure 1. Annual variation of (a) sunspot number  $R$  and (b) the corrected  $aa$  geomagnetic index for the years 1860–2006. The thin, vertical lines mark the sunspot minimum years and the numbers refer to the sunspot cycles 10–23. Notice that most cycles have their largest  $aa$  index after sunspot maximum (except cycles 12 and 13) and their minimum  $aa$  index value either in the sunspot minimum year or the year following the sunspot minimum year (except cycle 21).

Figure 2 shows the scatterplot of  $aa$  versus  $R$  for 1868–2006. All  $aa$  values are found to lie either on or above the given diagonal line  $aa_R = 8.83123 + 0.06254R$ , where this equation is used to compute the leading sporadic component of the  $aa$  index (i.e., the solar cycle component).

Figure 3 depicts the residual  $aa_I = aa - aa_R$ , or the following recurrent interplanetary component, having removed the leading sporadic component. The residual is believed to be associated with recurrent high-speed streams from coronal holes, which typically are at their greatest extent after sunspot maximum.<sup>15</sup> Thin, vertical lines mark the sunspot minimum years; thick, vertical lines mark the sunspot maximum years; and the numbers 11–23 again refer to the sunspot cycles. For all cycles, except cycles 12 and 13, the maximum value of the residual, denoted here as  $(aa_I)_{max}$ , occurs after sunspot maximum and ranges in value between 10.5 (cycle 14) and 24.3 (cycle 23), having a 90% prediction range of  $16.7 \pm 7.4$ .

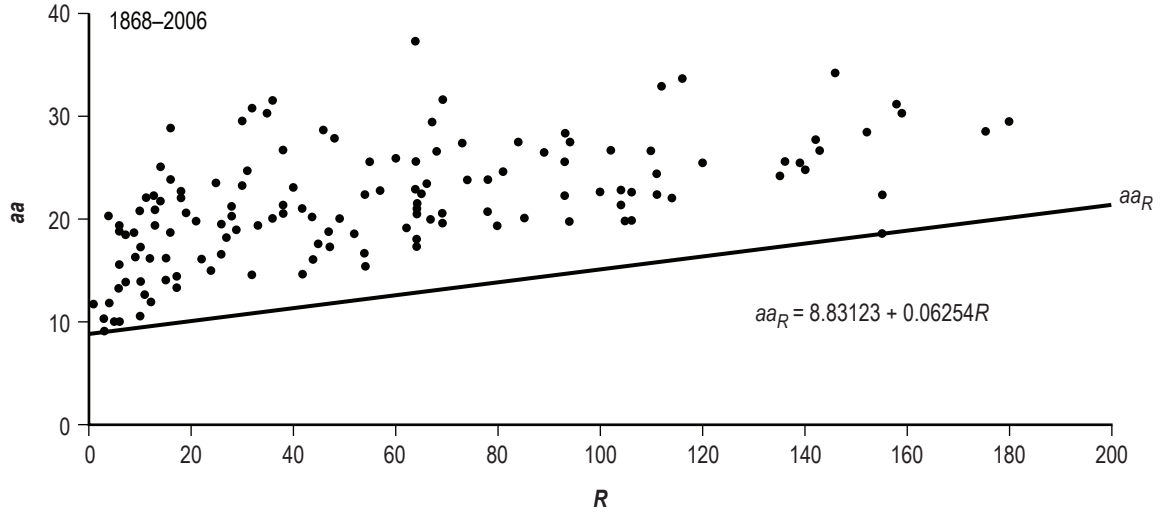


Figure 2. Scatterplot of the annual  $aa$  index values against  $R$  for the years 1868–2006. Notice that all  $aa$  index values lie on or above the line denoted  $aa_R$ , which is used to compute the leading sporadic component of the  $aa$  index (i.e., the solar cycle component).

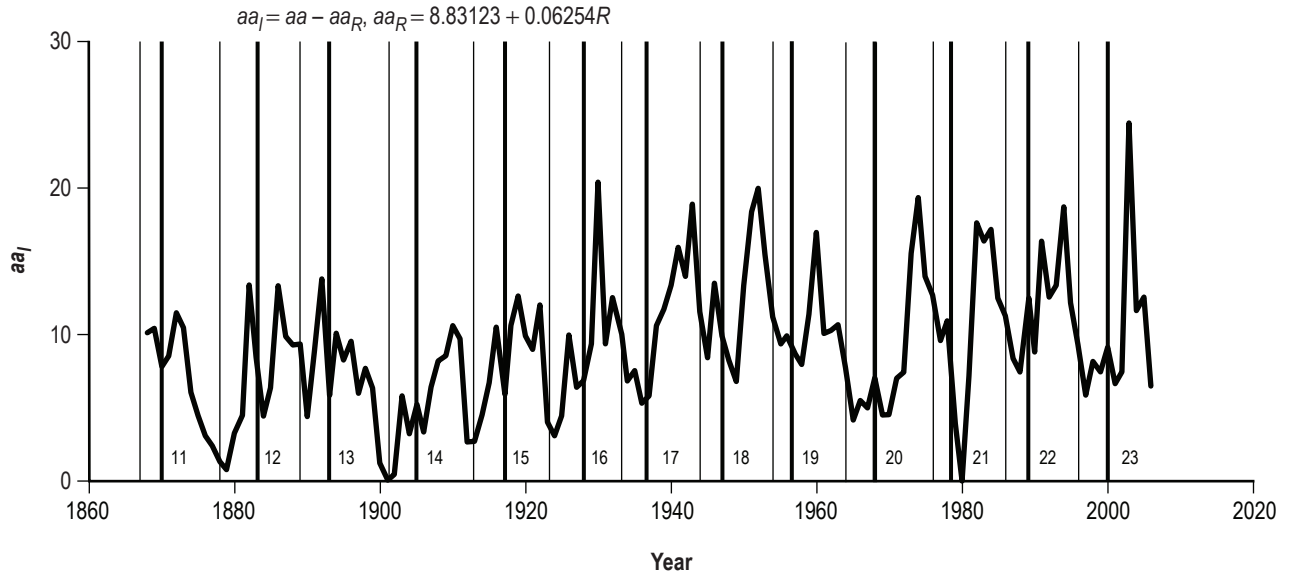


Figure 3. Annual variation of the residual or following recurrent interplanetary component of the  $aa$  index, computed as  $aa_I = aa - aa_R$  for the years 1868–2006. The thin, vertical lines mark the sunspot minimum years; the thick, vertical lines mark the sunspot maximum years; and the numbers refer to the sunspot cycles 11–23. Plainly, the maximum recurrent component of the  $aa$  index usually occurs after sunspot maximum (except cycles 12 and 13). Notice that the largest observed value of the recurrent component (24.3) occurred in 2003 during the decline of cycle 23.

Figure 4 plots the annual variation of  $R$ ,  $aa$ ,  $aa_I$ , the solar wind speed  $v$  (in  $\text{km s}^{-1}$ ), and the number of hours of solar wind observation (plots (a)–(e), respectively) for the interval 1950–2006. As before, thin, vertical lines mark the sunspot minimum years; thick, vertical lines mark the sunspot maximum years; and the numbers refer to solar cycles 19–23. Solar wind data are available for 1964–present, adapted here using the Omni-merged, 1-hr, 1 AU IP data (available at <http://cdaweb.gsfc.nasa.gov>).<sup>13</sup> In particular, the annual solar wind speed used in this study is the average of the maximum and minimum hourly solar wind speeds for each day, weighted by the number of hours of daily observation. As an example, on January 1, 1964, solar wind speeds were recorded for 12 hr, having a maximum of  $370 \text{ km s}^{-1}$  and a minimum of  $310 \text{ km s}^{-1}$ , thereby, inferring an average of the extremes of  $340 \text{ km s}^{-1}$ . Observations are available for 29 of the 31 days of the month covering 558 hr (75% coverage). The average of the daily maximum-minimum averages, weighted according to the number of hours of daily observation, was  $369 \text{ km s}^{-1}$  and this value represents the average solar wind speed for January 1964. For the remainder of the year, the average monthly solar wind speed/numbers of hours of observation were 352.9/228 (February), 0/0 (March–June), 517.5/111 (July), 453.6/159 (August), 463.4/237 (September), 459.8/396 (October), 430.7/249 (November), and 396/183 (December). For the year 1964, the average solar wind speed was  $418.4 \text{ km s}^{-1}$  based on 2,121 hr of observation (24.1% coverage), and it is this solar wind speed (and number of hours of observation) that is plotted in figure 4 for the year 1964. Inspection of figure 4 clearly shows that the solar wind speed  $v$  peaks after sunspot maximum for all observed cycles (cycles 20–23; observations began in November 1963). Interestingly, the highest average solar wind speed occurred in 2003 ( $542.8 \text{ km s}^{-1}$ , based on 8,688 hr of observation or 99.2% coverage; coverage is greatest (>90% coverage) for the years of 1974, 1979–1981, and 1995–present), and the peak in solar wind speed for all cycles (except cycle 23) occurs 2 yr prior to the following cycle’s sunspot minimum year (cycle 23 actually has a secondary peak in 2005, measuring  $469.9 \text{ km s}^{-1}$  based on 8,689 hr of observation or 99.2% coverage).

Figure 5 shows the scatterplots of (a)  $aa$  versus  $v$  and (b)  $aa_I$  versus  $v$  for 1964–2006. Plainly, both  $aa$  and  $aa_I$  tend to increase in value as solar wind speed increases. Both correlations are statistically very significant, with the stronger one being between  $aa_I$  and  $v$ . The inferred correlation has a coefficient of determination  $r^2=0.748$ , implying that nearly 75% of the variance can be explained by the inferred regression. So, the peaks observed in the  $aa$  and  $aa_I$  indices late in the cycle (after solar maximum) appear to be directly related to increased solar wind speed, which probably is the result of high-speed streams from coronal holes.<sup>15–21</sup>

Figure 6 depicts (a) the cyclic variation of sunspot number  $\langle R \rangle$ , (b) the  $aa$  geomagnetic index  $\langle aa \rangle$ , (c) the following recurrent component  $\langle aa_I \rangle$ , and (d) the solar wind speed  $\langle v \rangle$  for cycles 11–23, where each cyclic average is computed from sunspot minimum to subsequent cycle sunspot minimum. (Cycle 23 is presumed to have ended in 2006 on the basis of annual averages.) For the first three parameters, all reveal a long-term increase over time, such that for cycle 24, the next cycle, one infers  $\langle R \rangle = 82.6 \pm 27.6$ ,  $\langle aa \rangle = 26 \pm 4.3$ , and  $\langle aa_I \rangle = 12 \pm 2.8$ , these estimates being the 90% prediction intervals. Thus, there is a 95% probability that cycle 24 will have  $\langle R \rangle \geq 55$ ,  $\langle aa \rangle \geq 21.7$ , and  $\langle aa_I \rangle \geq 9.2$ . Because of the close relationship between solar wind speed and, in particular,  $aa$  and  $aa_I$  (fig. 5), the cyclic average of solar wind speed is inferred to have increased over time, as well. (Strictly speaking, the cyclic variation of solar wind speed  $\langle v \rangle$  is indeterminate because of the brevity of the solar wind record, 1964–present, especially, as compared to the solar/geomagnetic record, which is considered reliable since the mid 1800s.)

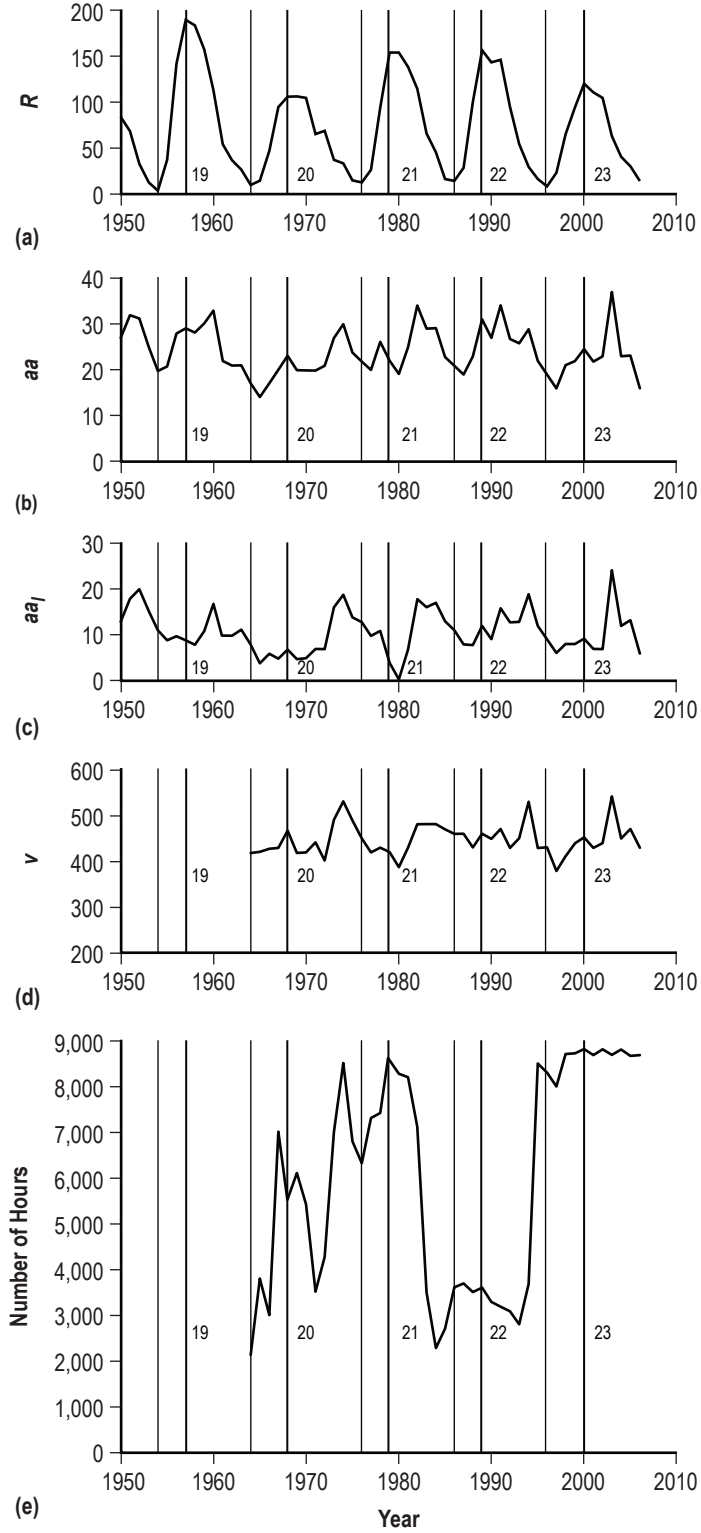


Figure 4. Annual variation of (a)  $R$ , (b)  $aa$ , (c)  $aa_I$ , (d) solar wind speed  $v$ , and (e) number of hours of solar wind observations for the years 1950–2006. The thin and thick vertical lines and the numbers 19–23 have the same meanings as before. See text for details.



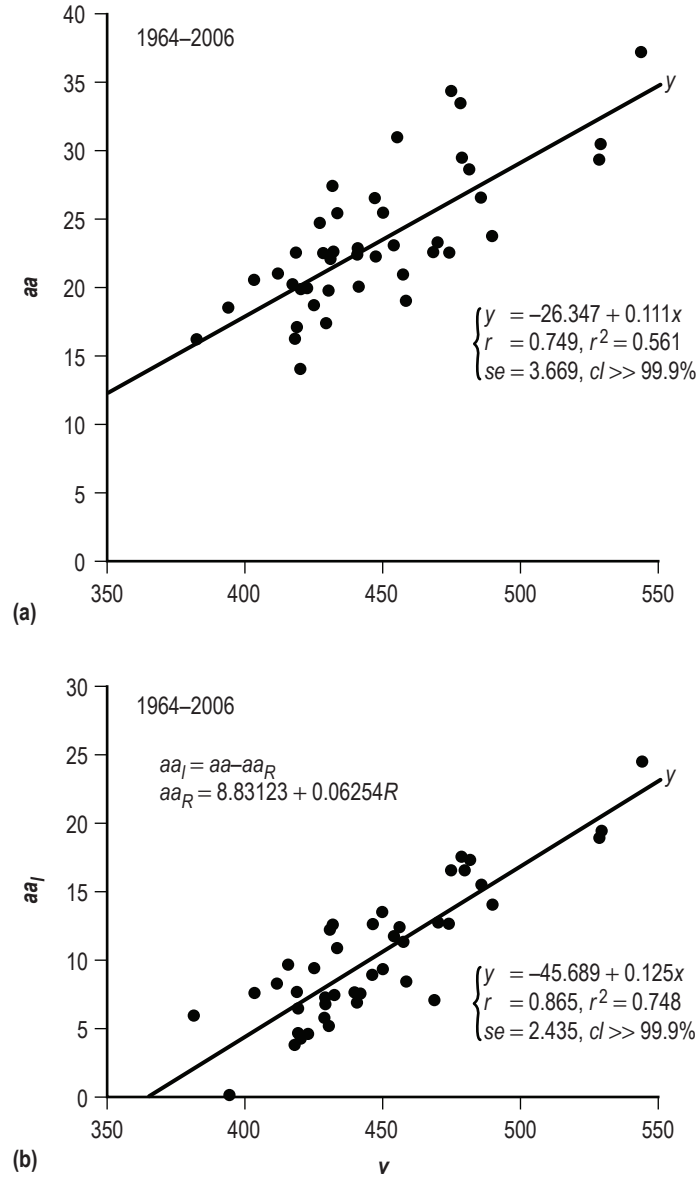


Figure 5. Scatterplots of (a)  $aa$  and (b)  $aa_I$  versus  $v$  for the years 1964–2006. See text for details.

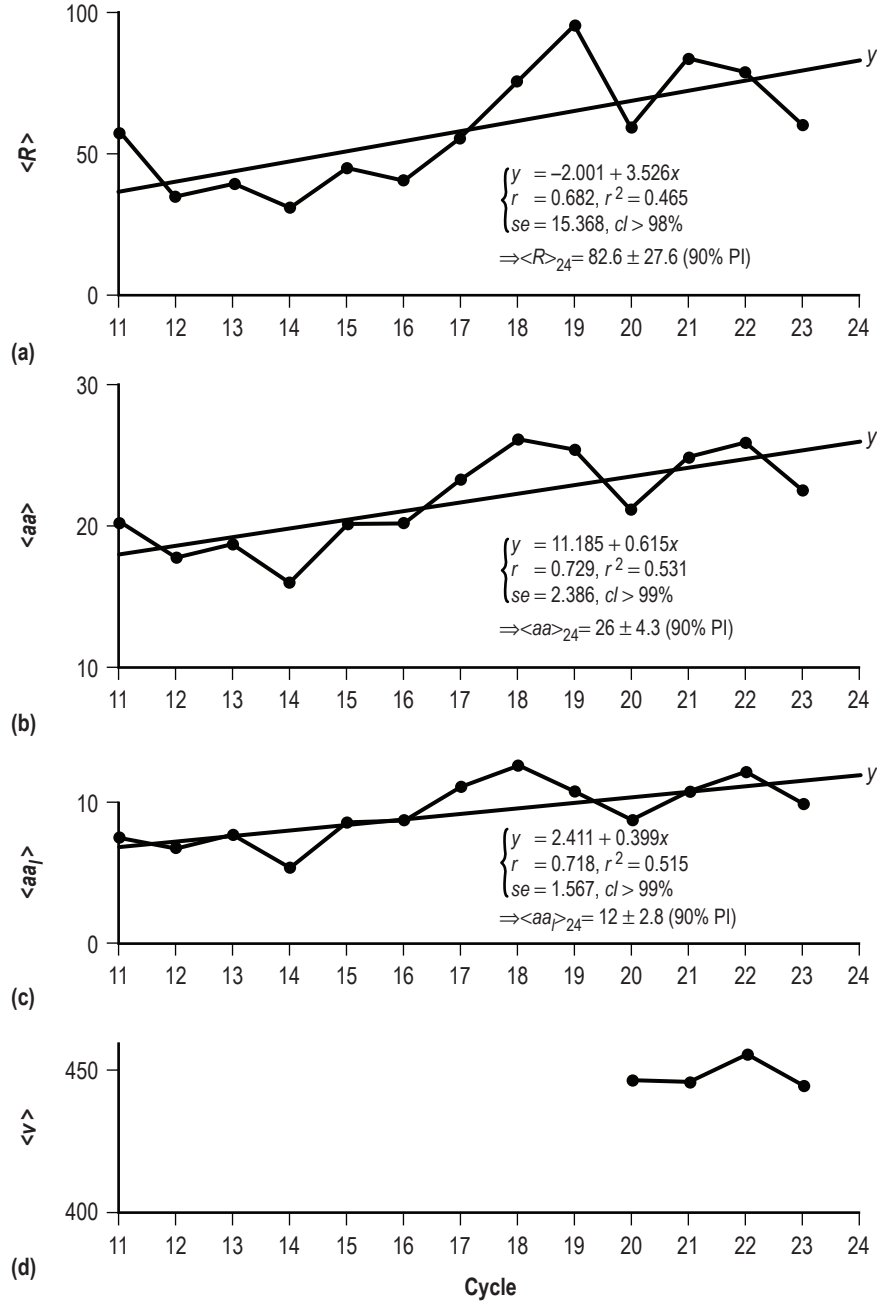


Figure 6. Cyclic variation of (a)  $\langle R \rangle$ , (b)  $\langle aa \rangle$ , (c)  $\langle aa_I \rangle$ , and (d) and  $\langle v \rangle$  for cycles 11–23. See text for details.

### 3. SUMMARY

This study has shown that, on the basis of annual averages, solar wind speed is directly related to both the geomagnetic and solar cycles. Higher (lower) solar wind speed associates with higher (lower) values of the *aa* index, especially for the residual or following recurrent component of the *aa* index. Because there has been a long-term increase in the strength of the solar/geomagnetic cycles over time (cycles 11–23), it is inferred that the solar wind speed has also experienced a long-term increase.

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